Control and protection challenges in fully metallic tokamak WEST for long pulse operation

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The WEST tokamak

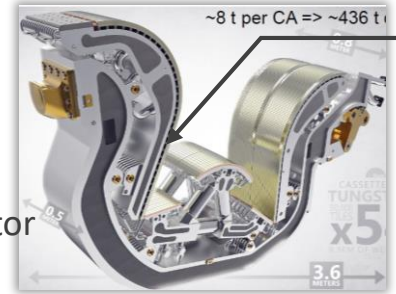
▶ **WEST is a mid-size superconducting tokamak operated in a fully metallic environment (W)**

I_p (q_{95}~2.5)	1.0 MA
B_φ	3.7 T
R / a	2.5 / 0.5 m
V_p	15 m^3
P_{add}	16 MW (9+7) *(+3 ECRH >= 2024)*
$T_{flattop}$	1000 s

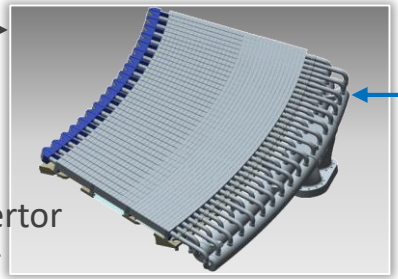
▶ **WEST key missions are twofold:**

- Paving the way towards the ITER actively cooled tungsten divertor procurement and operation
- Mastering integrated scenarios **over relevant plasma wall equilibrium time scale** in a metallic environment

ITER divertor cassette

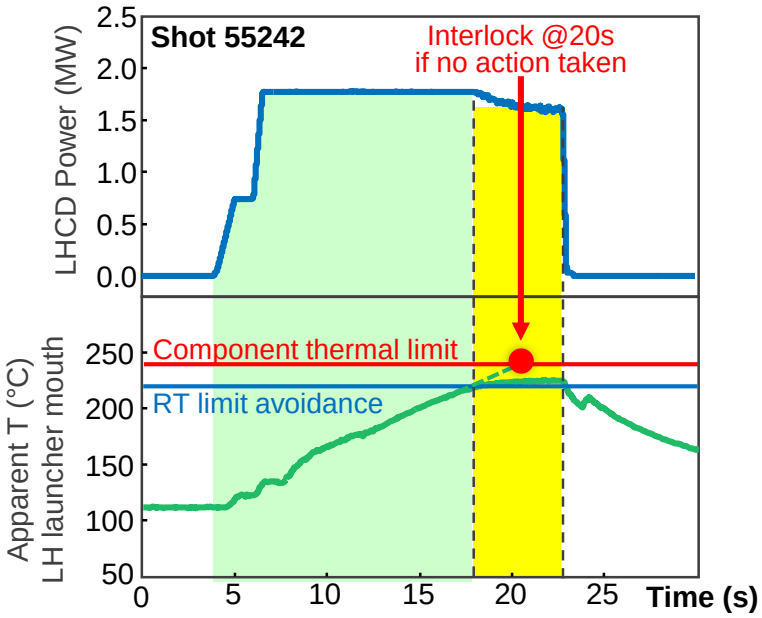


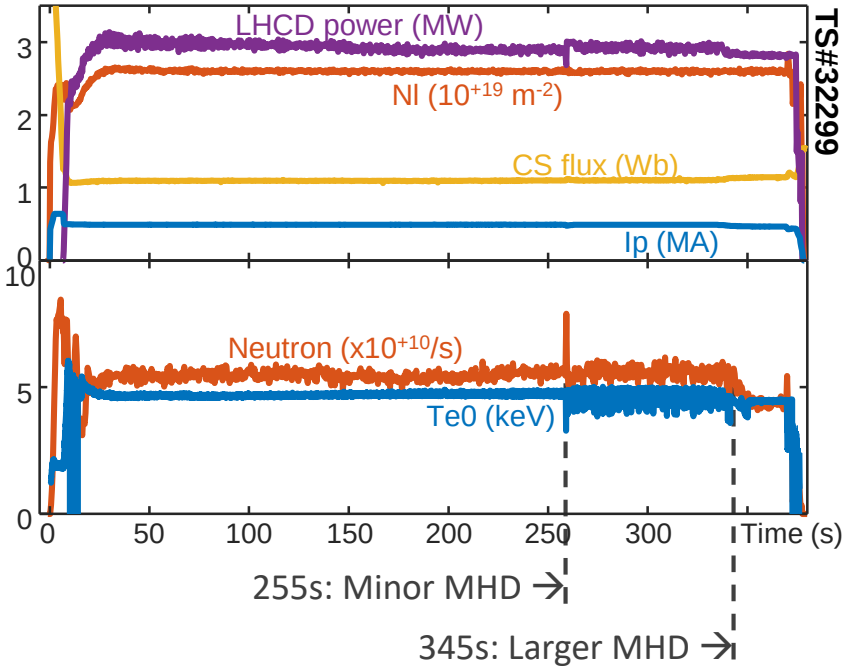
WEST divertor sector



WEST lower divertor (12 sectors)

Long pulse operation requires specific management





Plasma operation on short time scale (~10 seconds) might not reach any limit.
Situation might differ on longer time scale (minutes, hours)

- **Purpose: being able to pursue the discharge**
- **Solution: dealing with unexpected events on RT (e.g. apply predefined strategies)**

Outline

- Concepts for long pulse operation / implementation on WEST
- Scenario design in terms of operation and plasma control
- Machine protection
- Future developments

- **Concepts for long pulse operation / implementation on WEST**
- Scenario design in terms of operation and plasma control
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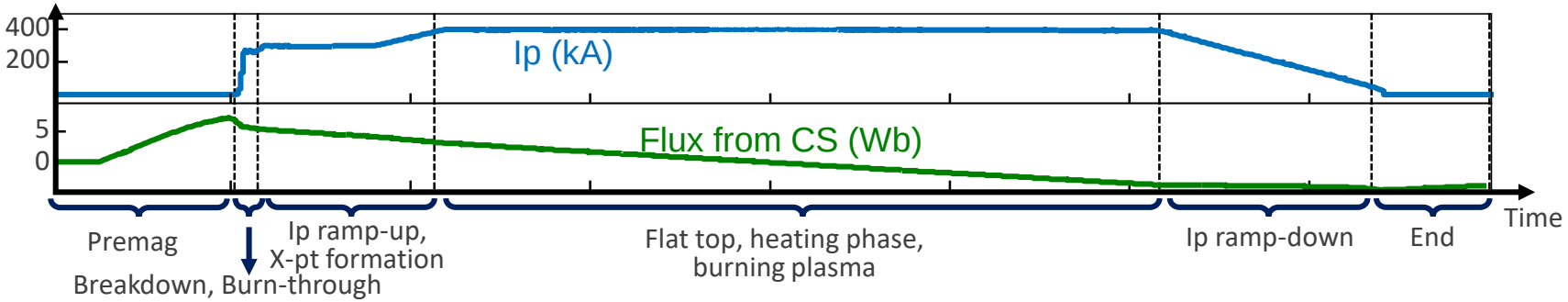
Key concepts in order to deal with unexpected events

- Plasma discharge = set of consecutive phases (segments)



- Event mitigation strategies: stage approach based on 4 levels

Event detection

→ Plasma scenario

Plasma state transition (MHD, H/L transition, instabilities, impurities, etc.)

→ Plant systems

Temporary unavailability?
Total/partial unavailability?
Reduced accuracy, plant operation limits, etc.

→

Event identification

- Event classification
- Prioritization

→

Event handling

1- Brief adjustment before coming back to ref. scenario

2- Slightly degraded plasma vs ref. (within a preset envelope)

3- Switch to plasma backup scenario (change segment)

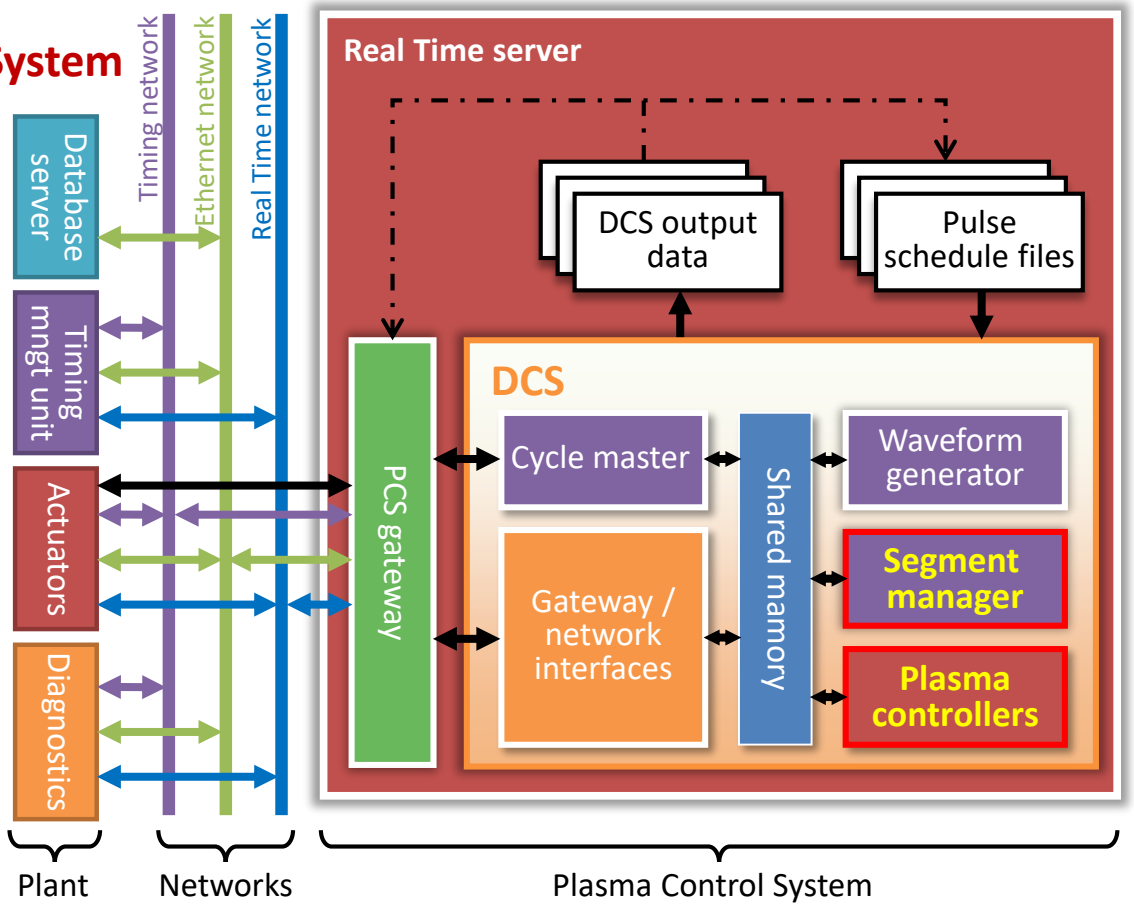
4- Trigger a Soft / Fast plasma shutdown

Plasma controller

Segment Manager

Main features of the Plasma Control System

- Based on DCS (Discharge Control System) developed at IPP for ASDEX-upgrade and configured for WEST
- Plasma controllers developed and validated in Matlab Simulink. Automatic C++ code generation and implementation.
- Segment oriented and event management natively implemented (**segment manager / Waveform generator**). Switch to another segment when outside plasma scenario envelop
- Specific Pulse Schedule Editor is used to prepare the plasma discharges



Xedit: specific Pulse Schedule Editor

- The IPP W7-X Pulse Schedule Editor Xedit configured for WEST needs
- Segment management layer is used to trigger a new segment on event detection
  - List of event and policies specified: duration, MHD, communication issue, parameter outside predefined envelop, etc.
  - E.g. specific plasma termination designed for: flux limit, runaway detection, network communication lost, etc.
  - Offer flexibility to address new events

List of events resulting in triggering a new segment

Set of segments used to build a plasma discharge

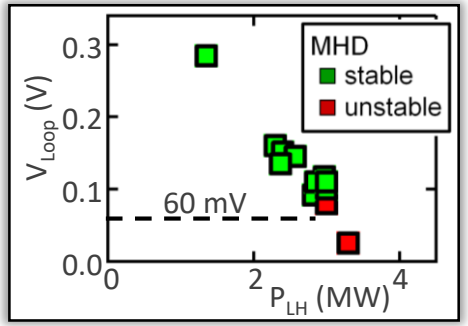
		[1] Premag		[4] Limiter	[5] Xformation		[6] Flat ...	[7] Ram...
		[1.1]	[1.2]	[4.1]	[5.1]	[5.2]	[6.1]	[7.1]
WEST_SegmentManagement	unit		[1.2]	[4.1]	[5.1]	[5.2]	[6.1]	[7.1]
Segment characteristics								
Segment identifier			1	5	6	7	8	9
Transition time	s		0.0	0.1	0.1	0.5	0.5	0.5
Segment duration	s		10.0	0.83	0.12	1.0	5.0	3.0
Next segment to trigger			-1	6	7	8	9	996
Plasma phase event			Disable	Disable	Disable	Disable	Disable	Disable
Plasma current control failed event			Disable	Enable	Enable	Enable	Enable	Enable
Magnetic control failed event			Enable	Enable	Enable	Enable	Enable	Enable
Fueling control failed event			Disable	Enable	Enable	Enable	Enable	Disable
LHCD system failed event			Disable	Disable	Disable	Disable	Disable	Disable
ICRH system failed event			Disable	Disable	Disable	Disable	Disable	Disable
Cu High Impurity level detection event			Disable	Disable	Disable	Disable	Disable	Disable
Fe High Impurity level detection event			Disable	Disable	Disable	Disable	Disable	Disable
W High Impurity level detection event			Disable	Disable	Disable	Disable	Disable	Disable
Disruption detection event			Disable	Enable	Enable	Enable	Enable	Enable
High MHD level event			Disable	Disable	Disable	Disable	Disable	Disable
Calorimetry protection event			Disable	Disable	Disable	Disable	Disable	Disable
LPA protection event			Disable	Disable	Disable	Disable	Disable	Disable
ARRPREM event			Enable	Enable	Enable	Enable	Enable	Enable
Plasma current end event			Disable	Enable	Enable	Enable	Enable	Enable
End of flux event			Disable	Enable	Enable	Enable	Enable	Disable
Poloidal overheating event			Disable	Disable	Disable	Disable	Disable	Disable
High radiated power ratio event			Disable	Disable	Disable	Disable	Disable	Disable
Limiter to X point Transition			Disable	Disable	Disable	Disable	Disable	Disable
X point to Limiter Transition			Disable	Disable	Disable	Disable	Disable	Disable
L to H mode transition			Disable	Disable	Disable	Disable	Disable	Disable
H to L mode transition			Disable	Disable	Disable	Disable	Disable	Disable
Generic Timing System event 1			Enable	Enable	Enable	Enable	Enable	Enable
Generic Timing System event 2			Enable	Enable	Enable	Enable	Enable	Enable

- Goal: stay within the operation envelop while ensuring the plasma scenario / Performance

- Concepts for long pulse operation / implementation on WEST
- **Scenario design in terms of operation and plasma control**
- Machine protection
- Future developments

Limitations due to the central solenoid

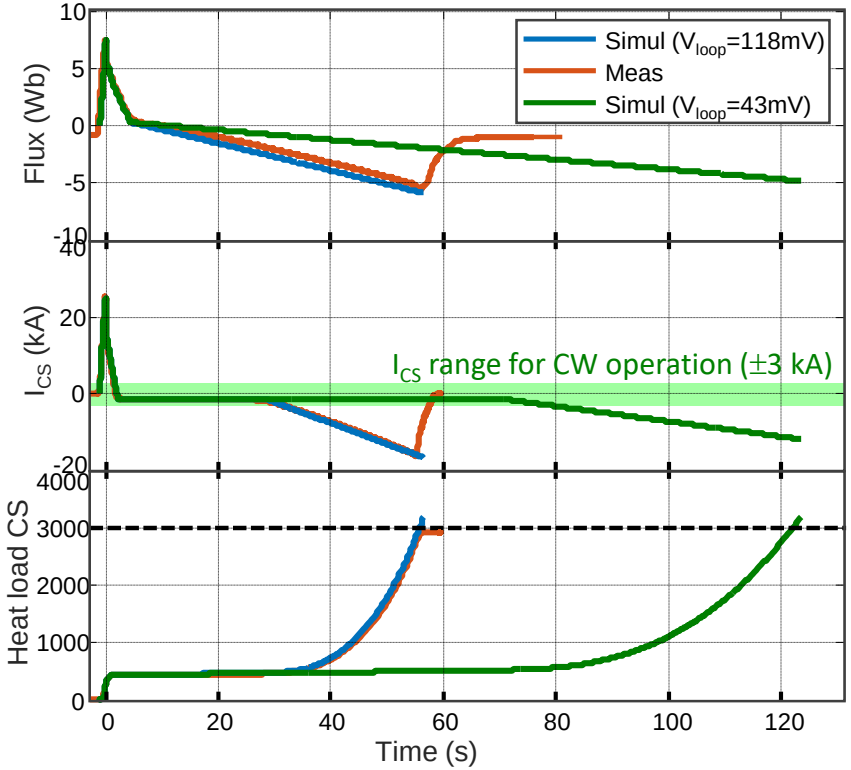
- WEST TF coils are superconducting,
  WEST PF and CS are made of Cu actively cooled
- Total flux swing available CS + iron core: 14 Wb
  (CS current: 40 kA ➘ -30 kA)
- Model of flux consumption done to identify limitation
- Tiny range of current in CS for CW operation (±3 kA)
- Main limitation in the CS due to heat load in the coil **NOT** due to the flux swing available.
  ~120s achievable with Vloop~45mV or 60mV (optimized startup phase)



[P. Maget]

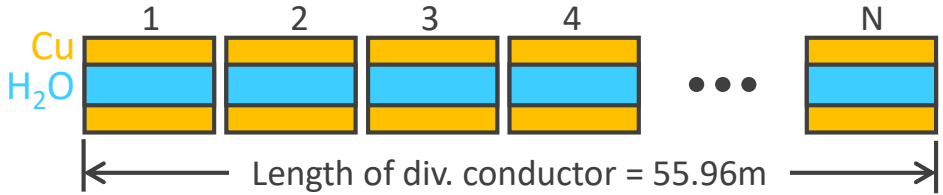
- Longer Duration (> 120 s): obtained for V_{loop} ~ 0 V **AND** transition when the CS current is in the range ±3 kA
  ➔ **adjust plasma scenario**

WEST #55786: Ip=400 kA; USN; dX=7cm;
P_{LH}=3 MW; Nl=3.3 $10^{+19}m^{-2}$; **Duration 55s**



Limitations due to the divertor coils

- Divertor coils made of Cu actively cooled
- Finite element cooling model implemented in real time

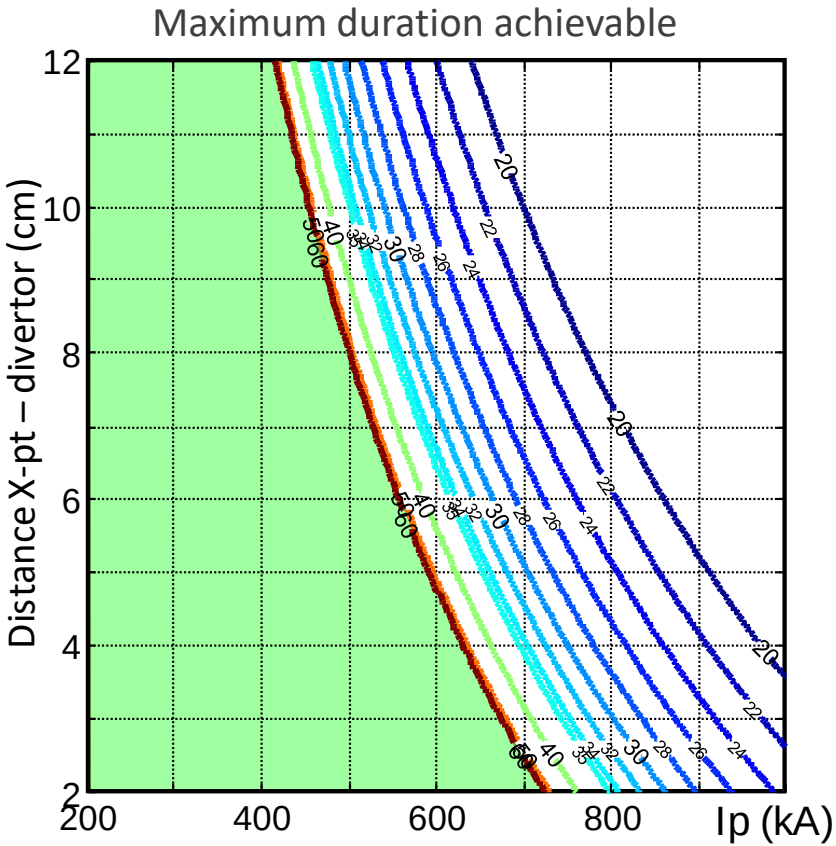


$$T_{Cu}(i) = T_{Cu}(i) - \alpha\,[T_{Cu}(i) - T_{H2O}(i)]\,\Delta t + \beta\, I_{div}^2$$

$$T_{H2O}(i) = (1-\gamma)\,T_{H2O}(i) + \gamma\, T_{H2O}(i-1) + f(T_{Cu} - T_{H2O})\,\Delta t$$

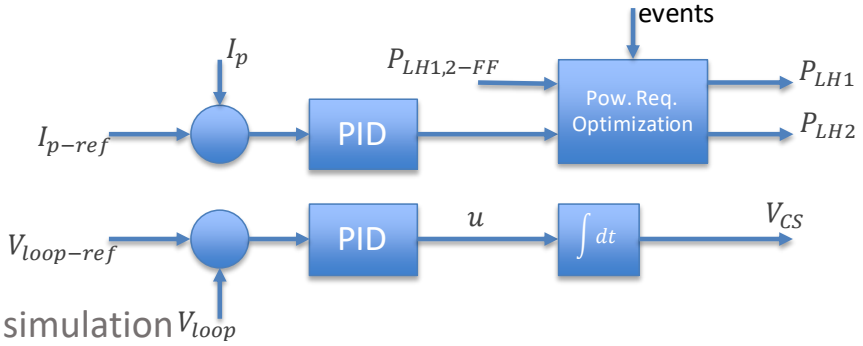
$$T_{H2O}(0) = T_{input} = 50 \text{ or } 70°C \qquad T_{ouput} < 100°C$$

- Max CW current in the divertor coils 12.5 kA
- No continuous operation for Ip > 700 kA



Control of Ip and loop voltage

- Implemented control
  - I_p controlled through LHCD power
  - V_{loop} controlled through V_{CS}



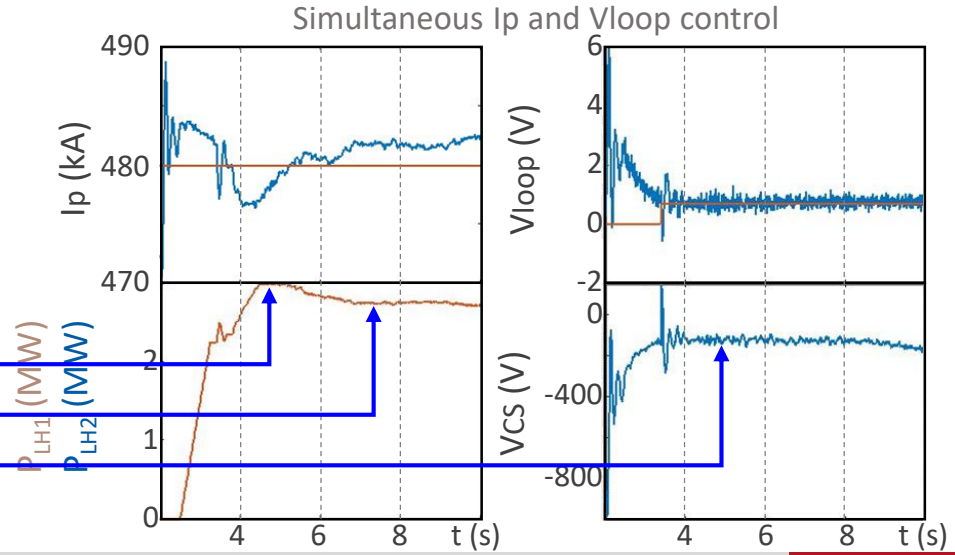
- Controller not yet validated on plasma but tested on simulation
  - Magnetic controller same as on the tokamak
  - Heating controller same as on the tokamak
  - FEEQS + 0D model of flux consumption (parameters tuned to fit with the pulse data)

- Example based on shot 56727: I_p=480kA
  Switch ON controller at 3 s: V_{loop} = 0.1V

Saturated LHCD power to a prescribed value

~2x2.8 MW needed to sustain I_p=480kA with V_{loop} = 0.1V

Control CS voltage to obtain V_{loop} = 0.1V



- Concepts for long pulse operation / implementation on WEST
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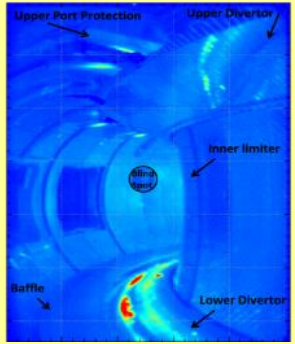
Machine protection based on infrared diagnostic

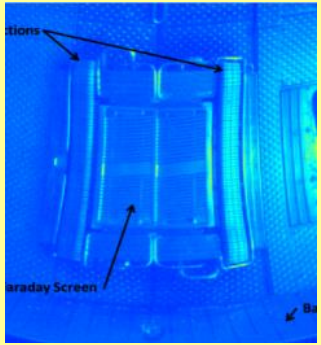
- IR: Extensive coverage of the in-vessel components

Wide Angle



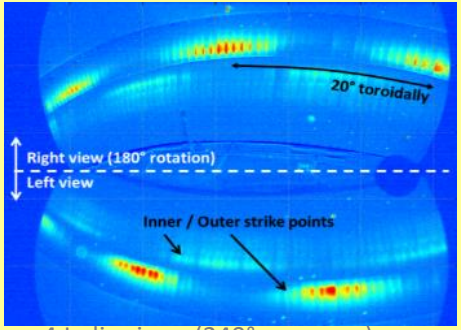
Field of View 60°

Antennas (x5)



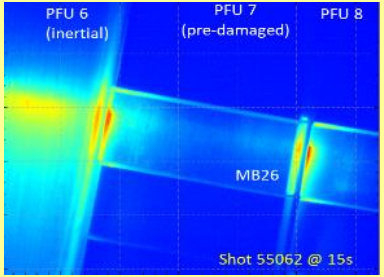
5 antennas views

L-divertor



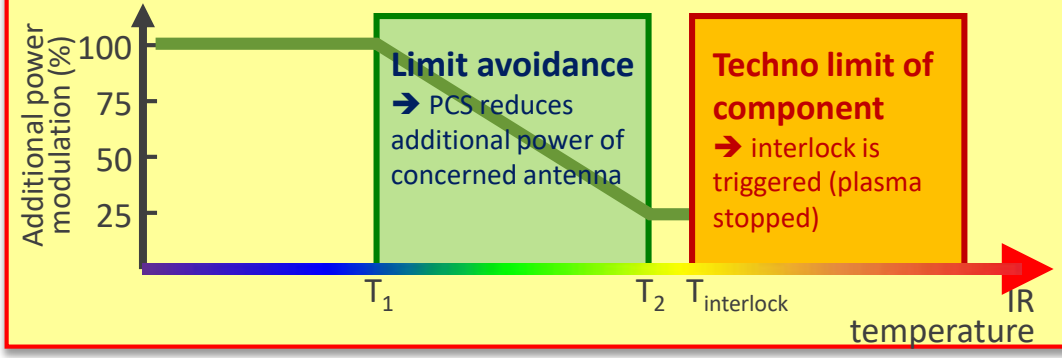
4 L-div views (240° coverage)
Full coverage in phase 2

Very High Resolution



1 L-div views, 0.1 mm/pixel
Movable Field of View

- Principle of the protection: interlock and limit avoidance



WEST capabilities

11 IR cameras (3.9 µm, $\delta\lambda$=200 nm) on WEST

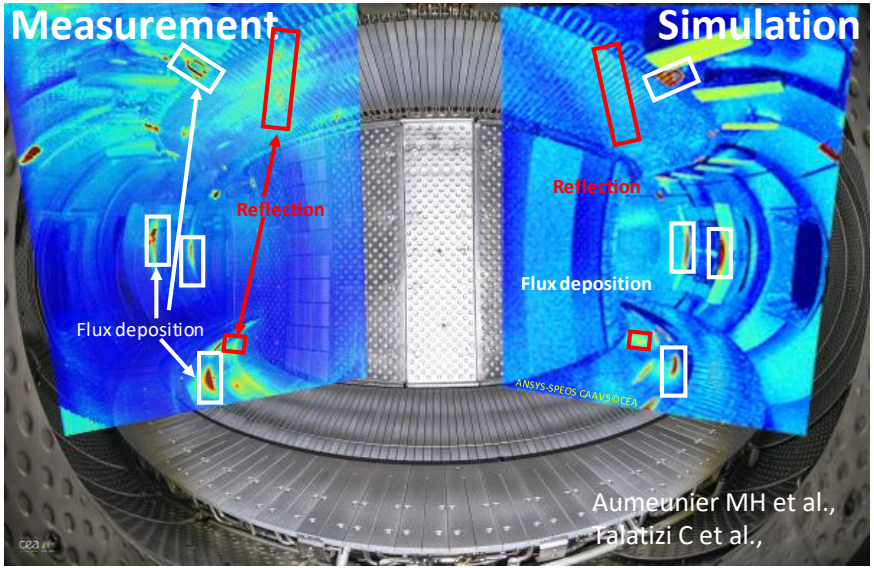
99% of availability. Additional power limited to 1MW – 1s without the IR diagnostic

35 Regions of interest monitored 12 on real time

T_2-T_1 = 50°C; $T_{interlock}$=T_2

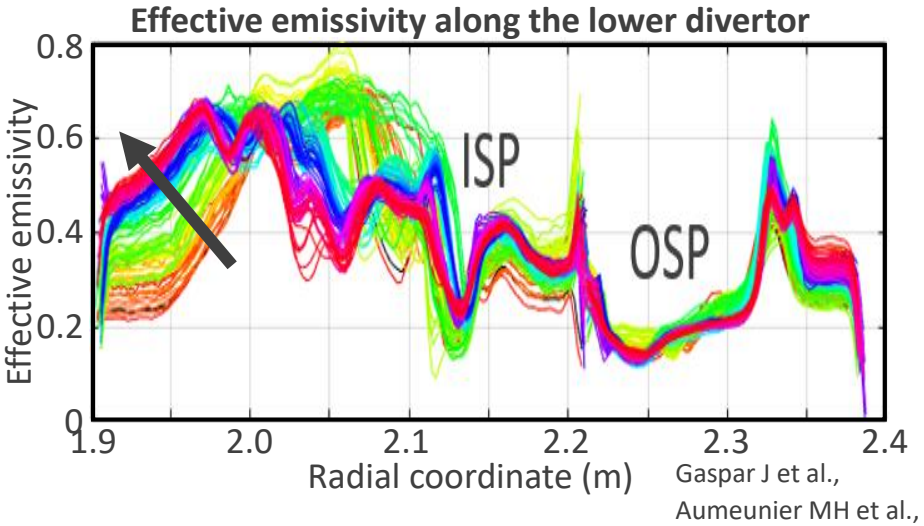
Essential step in protection: simulation in order to understand the videos

- Image interpretation based on scene modeling including reflections



- Prediction of deposited & reflected fluxes from the magnetic equilibrium

- Evaluate real temperature from apparent temperature and emissivity

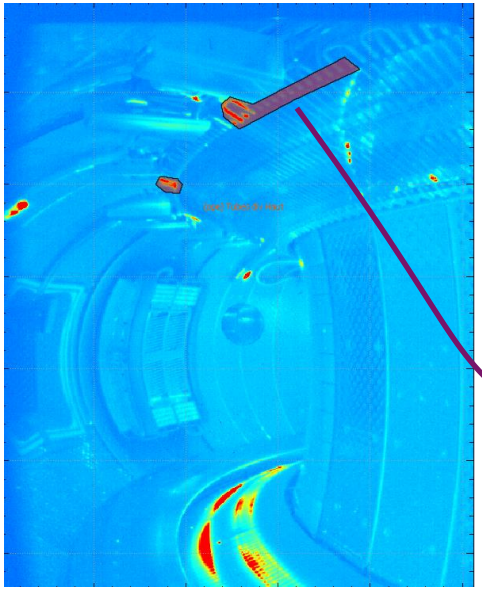


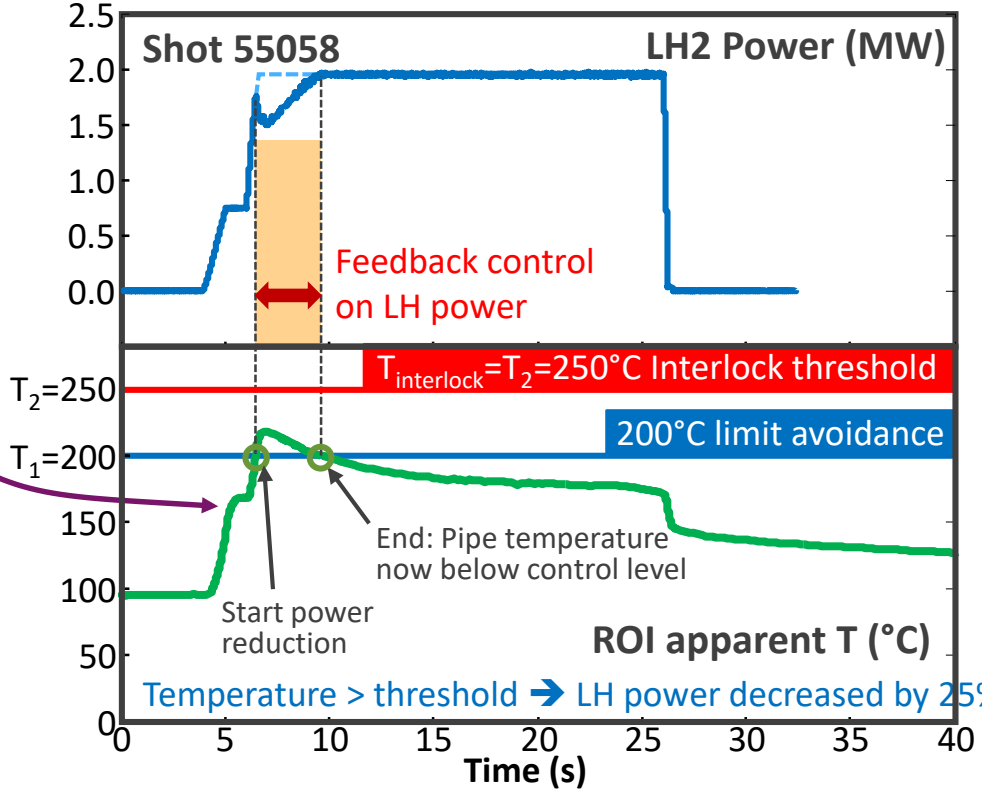
- Large variations of the divertor emissivity

- Emissivity ~0.15 and remains constant at the ISP and OSP positions (similar to pre-exposition values)

Example: IR based thermal protection of PFC

- Overheating of ripple protection. Results in LHCD power decrease. No effect on ICRH

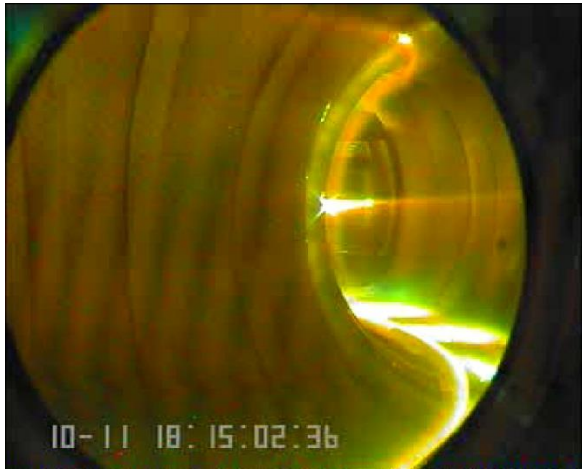


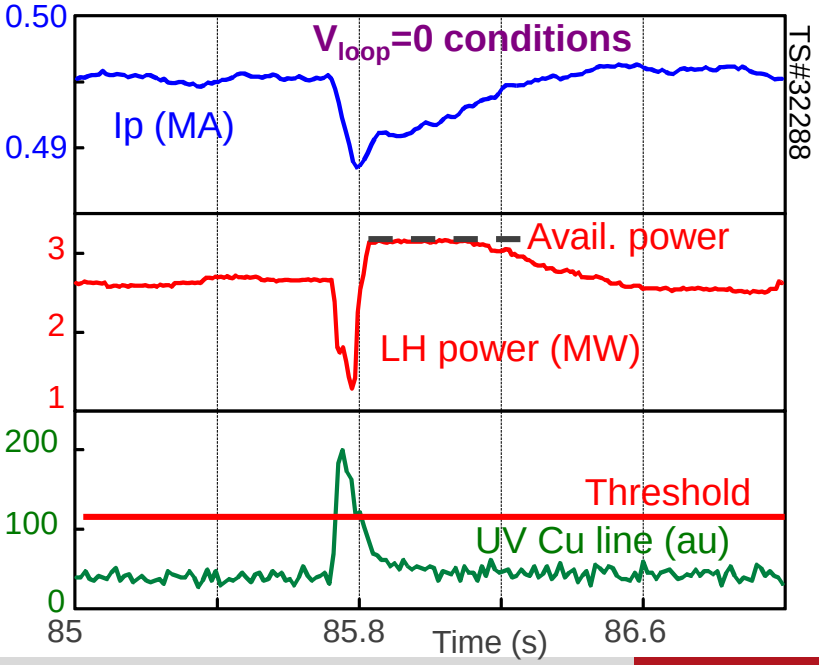


Temperature > threshold ➔ LH power decreased by 25% by PCS

Protection based on VUV measurements

- High content of metallic impurities Cu, Ag and/or Fe might be a sign of an on-going damage of an in-vessel component
- Copper is only present on the LHCD launcher: if Cu content > prescribed value then LHCD power is reduced until proper level is recovered
- if Fe content > prescribed value then LHCD AND ICRH powers are reduced until proper level is recovered
- When the event is mitigated, the power comes back to the nominal value





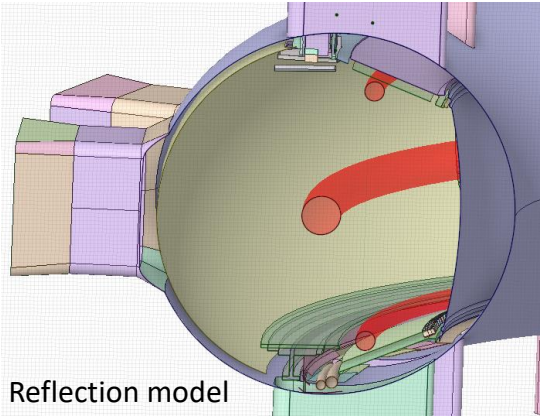
Wall heat flux control based on model and combination of diagnostics

Magnetics
ICRH heating
LHCD heating
Bolometry

Power distribution models

Wall Reflection models

- Heat flux density on divertor (Max 10 MW/m²)
- Total thermal load (Max 10 MW)
- Energy deposited on unsupervised area (Max VV below 2.2MJ/m²)

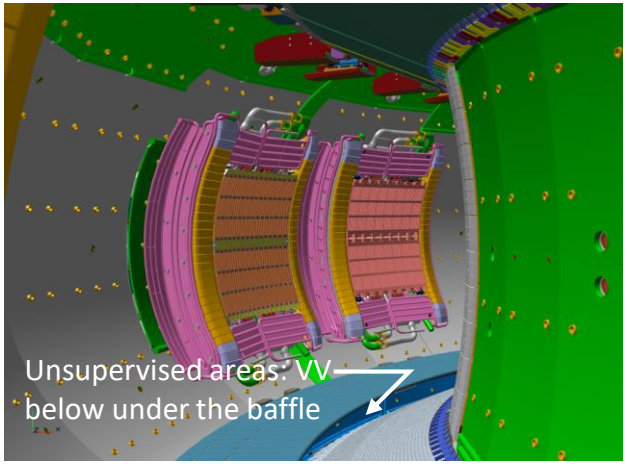


$$q^{osp}_{deposited} = r^{out} \times r^{ripple} \times \frac{P_{cond}}{2\pi R^{osp}\, \lambda_q^{omp} \frac{B^{omp}_{poloidal}}{B^{omp}_{total}}} \times \frac{\left\| \vec{B}^{osp}_{total} \wedge \vec{n}^{osp}_{divertor} \right\|}{\left\| \vec{B}^{osp}_{total} \right\|}$$

Fixed 2/3

Fixed 2

Fixed 6.5mm



- **Allow:**
  - processing heat loads on supervised and unsupervised areas
  - Ensure machine protection wrt thermal loads
  - Control flux density on divertor for qualification under well controlled and reproducible conditions

- Concepts for long pulse operation / implementation on WEST
- Scenario design in terms of operation and plasma control
- Machine protection
- **Future developments**

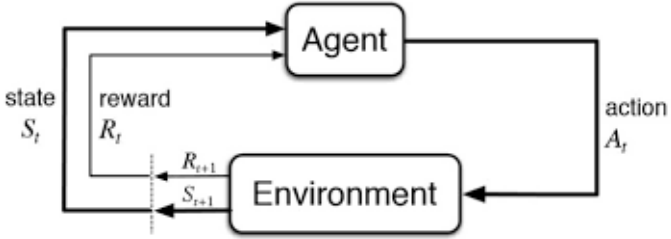
Artificial Intelligence (AI) for long pulse operation of WEST

- **New field in fusion. Allows working on complex use-cases where data or models tend to be limited. Machine learning could enable applications from fast plasma simulations to non-linear feedback control.**

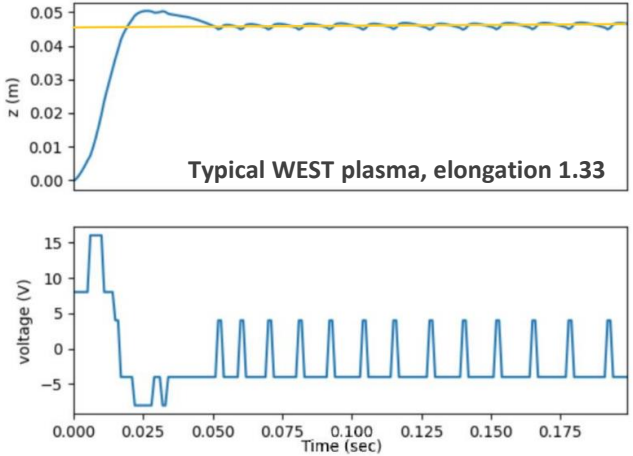
- **Several ongoing applications are studied at the IRFM:**
  - Fast detection of hot spots through infrared video signals, UFOs, etc.
  - Magnetic control based on [1]

- **Two paradigms are at the core of those methods:**
  - Supervised learning uses datasets **to identify and generalize underlying phenomena in the data**
  - Reinforcement learning uses interactions with an environment through actions. **By trial and error, a « reward » signal is used by the agent to learn a given task**

On one hand, datasets are built on real shots, and on the other hand data are observed online within a simulation. Neural networks are used in both contexts.



Reinforcement learning



Control of plasma's vertical position on a linear and reduced vertical instability model.

[1] « Magnetic control of tokamak plasmas through deep reinforcement learning » - Degrave, J., Felici, F., Buchli, J. *et al.* - *2022*

Conclusion

- **Architecture of the WEST PCS and of the pulse schedule editor are designed to deal with events (segment approach of the discharge, event handling policies) and easily scalable**

- **Basic and more advanced plasma controls have been implemented:**
  - Magnetic Control of plasma current: only I_p or *(I_p , V_{loop})**
  - Magnetic Control of plasma position done on: $(R , Z)_{centroid}$ or (EROG , Z , dX) or *(EROG , Z , dSep)**
  - Fueling Control done on: VV pressure or plasma density (gas, SMBI and Pellets)
  - H&CD Control either feedforward or feedback (e.g. V_{loop} control)

- **Machine protection also implemented in the aim of pursuing safely the discharge**
  - IR protection based on measurement and reflection models
  - VUV spectroscopy measurements on Copper and Iron
  - Basic heat load modelled implemented on real time (allow the protection of unsupervised areas)
  - And also Runaway electron, interlock on subsystems or IR measurements

- **Future activities**
  - Implement/test control based on AI for the plasma shape, the path toward a prescribed plasma state (e.g. V_{loop}=0)
  - Improve the actuator management with equivalence rules between them (H&CD systems, valves, etc.)
  - Availability of ECRH in 2024 will allow more flexibility and will require control developments e.g. to mitigate MHD, W core contamination, etc.
  - Ultimate target of WEST (cf. Project Plan) is to obtain long pulse discharge with 10 GJ of injected/extracted energy

** Still to be tested on plasma although validated on simulation*

Thank you for your attention